TRANSMITTING AND RECEIVING APPARATUS FOR SUPPORTING TRANSMIT ANTENNA DIVERSITY USING SPACE-TIME BLOCK CODE

PRIORITY

5   This application claims priority under 35 U.S.C. § 120 to an application entitled "Full Rate Space-Time Block Codes For Complex Constellations" filed in the U.S. Patent and Trademark Office on October 10, 2002 and assigned Serial No. 60/417,466, the contents of which are incorporated herein by reference.   This application claims priority under 35 U.S.C. §119 to an application entitled

10   "Transmitting and Receiving Apparatus for Supporting Transmit Antenna Diversity Using Space-Time Block Code" filed in the Korean Intellectual Property Office on April 4, 2003 and assigned Serial No. 2003-21364, the contents of which are incorporated herein by reference.

15   **BACKGROUND OF THE INVENTION**

1. Field of the Invention

       The present invention relates generally to a wireless communication system, and in particular, to a transmitting and receiving apparatus using transmit antenna diversity to combat the degradation effects of fading.

20   2. Description of the Related Art

       One of effective techniques to mitigate fading is transmit diversity in a wireless communication system. Assuming that the channel characteristics of a receiver are known to a transmitter, a switched diversity technique has been proposed (J. H. Winters "Switched Diversity with Feedback for DPSK Mobile Radio

25   System", IEEE Trans. Veh. Technol., vol. 32, pp. 134-150, Feb. 1983) and a multivibrate modulation/coding has also been proposed (G. G. Raleigh and V. K. Jones, "Multivibrate Modulation and Coding for Wireless Communication", IEEE J.

Select. Areas. Commun., vol. 17, pp. 851-866, May 1999).

In practice, however, it is nearly impossible for the transmitter to have perfect instantaneous information about the characteristics of the receiver because of mobility and channel changes. Also, the use of feedback channels for reporting channel status information to the transmitter may not be desirable since it reduces channel capacity. Thus, many researchers have focused on the transmit diversity scheme assuming that the transmitter does not know channel information. An initial type of transmit diversity scheme was proposed by Wittneben (A. Wittneben, "Base Station Modulation Diversity for Digital SIMULCAST", in proc. IEEE'VTC, May 1993, pp. 505-511). Foschini studied layered space-time architectures for multiple transmit antenna systems (G. J. Foschini, Jr., "Layered Space-Time Architecture for Wireless Communications in a Fading Environment When Using Multi-element Antennas", Bell Labs Tech. J., pp. 41-59, Autumn 1996). In the presence of Gaussian Noise, Telatar analyzed the capacity of multiple antenna systems (E. Telatar, "Capacity of Multi-Antenna Gaussian Channels", AT&T-Bell Laboratories, Internal Tech. Memo., June 1995). Later, Foschini et. al. derived the expression of outage capacity under the assumption of quasi-static fading (G. J. Foschini, Jr. and M. J. Gans, "On Limits of Wireless Communication in a Fading Environment When Using Multiple Antennas", Wireless Personal Commun., vol. 6, pp. 311-335, 1998).

Recently, space-time coding has received increased attention due to its good performance for high-rate transmissions. Tarokh et. al. introduced space-time trellis coding that provides both coding gain and diversity gain (V. Tarokh, N. Seshadri, and A. R. Calderbanck, "Space-Time Codes for High Data Rate Wireless Communications: Performance Criterion and Code Construction", IEEE Trans. Inform. Theory, vol. 44, pp. 744-765, Mar. 1998, and V. Tarokh, N. Seshadri, and A. R. Calderbanck, "Space-Time Codes for High Data Rate Wireless Communications: Performance Criteria in the Presence of Channel Estimation Errors, Mobility, and

Multiple Paths", IEEE Trans. Inform. Theory, vol. 47, pp. 199-207, Feb. 1999). Particularly, the space-time trellis coding disclosed in the second thesis of Tarokh offers the best possible trade-off between constellation size, data rate, diversity advantage, and trellis complexity.

5   However, according to the above space-time coding techniques, the decoding complexity increases exponentially with transmission rate when the number of transmit antennas is fixed. Therefore, they are not feasible for a large of transmit antennas and at a high bandwidth efficiency.

To overcome this problem, Alamouti and Tarokh proposed space-time block
10 coding (S. M. Alamouti, "A Simple Transmit Diversity Technique for Wireless Communications", IEEE J. Select Areas Commun., vol. 16, pp. 1451-1458, Oct. 1998 and V. Tarokh, H. Jafarkhani, and A. R. Calderbandk, "Space-Time Block Codes from Orthogonal Designs", IEEE Trans. Inform. Theory, vol. 45, pp. 1456-1467, July 1999). These space-time block codes introduce temporal/spatial
15 correlation into signals transmitted from different transmit antennas, so as to provide diversity gain at the receiver and coding gain over an uncoded system. Despite the advantage of simple transmission/reception, these codes cannot achieve all possible diversity gains without data rate losses when complex symbols are transmitted through 3 or more antennas, due to the orthogonality condition for the columns of a
20 transmission matrix.

FIG. 1 is a block diagram of a transmitter using conventional space-time block coding. Referring to FIG. 1, the transmitter is comprised of a serial-to-parallel (S/P) converter 10, an encoder 20, and N transmit antennas 30-1 to 30-N. The S/P converter 10 groups every N symbols received from an information source (not
25 shown) into a block. The encoder 20 generates a predetermined number of symbol combinations from the N symbols and feeds them to the N transmit antennas 30-1 to 30-N for corresponding time periods.

FIG. 2 is a block diagram of a receiver that receives signals from the transmitter illustrated in FIG. 1. Referring to FIG. 2, the receiver is comprised of M receive antennas 40-1 to 40-M, a channel estimator 50, a multi-channel symbol arranger 60, and a decoder 70. The channel estimator 50 estimates channel
5 coefficients representing channel gains from the transmit antennas 30-1 to 30-N to the receive antennas 40-1 to 40-M. The multi-channel symbol arranger 60 collects symbols received from the receive antennas 40-1 to 40-M. The decoder 70 achieves a desired result by multiplying the symbols received from the multi-channel symbol arranger 60 by the channel coefficients, computes decision statistic for all possible
10 symbols using the result, and detects desired symbols through threshold detection.

In a communication system configured as illustrated in FIGs. 1 and 2, let $c_{i,t}$ be the symbol transmitted from transmit antenna i at time t and $a_{i,j}$ be the channel gain from transmit antenna i to receive antenna j. Then the signal $r_{i,j}$ received at receive antenna j at time t is given by equation (1):

$$r_{t,j} = \sum_{k=1}^{K} \sum_{i=1}^{N} a_{i,j} c_{i,t} + n_{t,j}$$

15

$$\ldots \ldots (1)$$

where k is a time index within each time period and $n_{t,j}$ is the noise for the channel between transmit antennas and receive antenna j at time t.
20   Assuming signals transmitted from different transmit antennas undergo independent Rayleigh fades, the channel gains $a_{i,j}$ are modeled as samples of independent complex Gaussian random variables with zero mean and variance of 0.5 per dimension and the noise values $n_{t,j}$ are modeled as samples of independent complex Gaussian random variables with zero mean and variance of $N_o/2$ per
25 dimension, where N_o is the noise spectral density.

An optimum space-time block code is designed so as to maximize the minimum coding gain of an error matrix. The error matrix refers to a matrix of the

differences between original symbols and erroneous symbols arranged in the receiver, and the minimum coding gain is the product of the eigen values of the error matrix.

5   For illustration, it is assumed that there are 2 transmit antennas and M receive antennas. The transmitter maps b input bits to one of 2^b complex symbols using a signal constellation with 2^b elements. At a first time period, 2b bits arrive at the encoder and constellation symbols s_1 and s_2 are picked up. The two symbols are formed with these constellation symbols and transmitted through the 2 transmit antennas for two time periods. The 2x2 transmission matrix is then shown in

10 equation (2):

$$S = \begin{pmatrix} s_1 & s_2 \\ -s_2^* & s_1^* \end{pmatrix}$$

$$\ldots\ldots (2)$$

where s_i^* denotes the conjugate of s_i.

      More specifically, the rows in the transmission matrix indicate symbols

15 transmitted at the same time and the columns indicate symbols transmitted from the same antenna. Thus, s_1 is transmitted from the first transmit antenna and s_2 from the second transmit antenna at time t, and $-s_2^*$ is transmitted from the first antenna and s_1^* from the second antenna at time t+1. This is the so-called Alamouti scheme and is an example of space-time block code.

20   Maximum likelihood (ML) decoding of the above space-time block code amounts to minimization of the decision metric of equation (3):

$$\sum_{m=1}^{M} \left(|r_{1,m} - a_{1,m}s_1 - a_{2,m}s_2|^2 + |a_{1,m}s_2^* - a_{2,m}s_1^*|^2 \right)$$

$$\ldots\ldots (3)$$

over all possible symbol pairs of s_1 and s_2. It can be shown that the above metric

25 decomposes into two parts, shown as equation (4), one of which

transmit antennas without loss in transmission rate (i.e., maximum diversity order) even if complex symbols are transmitted from 2 transmit antennas. To generalize the above scheme to more than 2 transmit antennas, a space-time block code in the form of a matrix of orthogonal columns provides a maximum diversity order. Examples of

5   these codes are shown in equation (6):

$$\begin{pmatrix} s_1 & s_2 & s_3 \\ -s_2^* & s_1^* & 0 \\ s_3^* & 0 & -s_1^* \\ 0 & s_3^* & -s_2^* \end{pmatrix} \begin{pmatrix} s_1 & s_2 & s_3 & 0 \\ -s_2^* & s_1^* & 0 & s_3 \\ s_3^* & 0 & -s_1^* & s_2 \\ 0 & s_3^* & -s_2^* & -s_1 \end{pmatrix}$$

$$\dots \dots (6)$$

The space-time block coding techniques including the Tarokh scheme using these transmission matrixes only reduces the transmission rate of one symbol per

10   channel in use to the transmission of 0.5 or 0.75 symbol per channel use, for more than 2 transmit antennas. This problem makes them less attractive for real wireless applications.

SUMMARY OF THE INVENTION

15   It is, therefore, an object of the present invention to provide a transmit diversity apparatus that provides a maximum transmission rate and a maximum diversity gain in a communication system using 3 or more transmit antennas.

It is another object of the present invention to provide a transmit diversity apparatus that provides a maximum diversity gain with a very simple encoding and

20   decoding structure in a communication system having using 3 or more transmit antennas.

It is a further object of the present invention to provide a transmit diversity apparatus that provides a maximum diversity gain in a communication system transmitting complex symbols through 3 or more transmit antennas.

The above objects are achieved by a transmitter and a receiver that support transmit antenna diversity using space-time block coding in a wireless communication system. The transmitter produces symbol combinations containing, as their elements, input symbols, the inversions and conjugates of the symbols, and

5   symbols obtained by rotating the phases of the symbols once, forms a matrix having symbols in at least two columns orthogonal to each other with the symbol combinations, and transmits the matrix. According to one aspect of the present invention, the receiver detects symbols that minimize ML decoding metrics over all possible symbols using channel gains from transmit antennas to a receive antenna.

10   According to another aspect of the present invention, the receiver selects candidate symbols among all possible symbols according to the characteristics of transmitted modulation symbols and detects symbols that minimize the ML decoding metrics.

BRIEF DESCRIPTION OF THE DRAWINGS

15   The above and other objects, features and advantages of the present invention will become more apparent from the following detailed description when taken in conjunction with the accompanying drawings in which:

FIG. 1 is a block diagram of a transmitter using conventional space-time block coding;

20   FIG. 2 is a block diagram of a receiver that receives signals from the transmitter illustrated in FIG. 1;

FIG. 3 is a block diagram of a transmitter that transmits symbols through 4 transmit antennas according to an embodiment of the present invention;

FIG. 4 is a block diagram of a transmitter that transmits symbols through 3

25   transmit antennas according to another embodiment of the present invention;

FIG. 5 is a block diagram of a receiver for performing decoding pursuant to an embodiment of the present invention;

FIG. 6A illustrates a BPSK (Binary Phase Shift Keying) signal constellation;

FIG. 6B illustrates a QPSK (Quadrature PSK) signal constellation;

FIG. 6C illustrates a 8PSK (8-ary PSK) signal constellation;

5   FIG. 7A illustrates a 16QAM (16-ary Quadrature Amplitude Modulation) signal constellation;

FIG. 7B illustrates a 64QAM (64-ary QAM) signal constellation;

FIG. 8 is a flowchart illustrating another embodiment of decoding according to the present invention;

10   FIG. 9 is a block diagram of a receiver for performing decoding according to the second embodiment of the present invention;

FIGs. 10A and 10B depict sub-optimal decoding according to the present invention;

FIG. 11 is a flowchart illustrating a third embodiment of decoding according 15 to the present invention;

FIG. 12 is a graph illustrating symbol error rate (SER) versus SNR (Signal to Noise Ratio) for 2, 3 and 4 transmit antennas transmitting BPSK codes;

FIG. 13 is a graph illustrating SER versus SNR for 2, 3 and 4 transmit antennas transmitting QPSK codes;

20   FIG. 14 is a graph illustrating SER versus SNR for 2, 3 and 4 transmit antennas transmitting 8PSK codes; and

FIG. 15 is a graph illustrating SER versus SNR for the first and third embodiments of decoding according to the present invention.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

Preferred embodiments of the present invention will be described herein below with reference to the accompanying drawings. In the following description, well-known functions or constructions are not described in detail since they would
5   obscure the invention with unnecessary detail.

The present invention is meant to provide a simple encoding and decoding structure that leads to a transmission matrix whose at least 2 columns are orthogonal to each other and provides a maximum diversity gain in a communication system adopting space-time block coding for 3 or more transmit antennas.
10

Transmission: Encoding

A transmitter generates a predetermined number of symbol combinations from another predetermined number of input symbols and forms a matrix with one symbol combination in each cell of the matrix. The transmission matrix varies
15   according to a modulation scheme and the number of transmit antennas. Symbols in row (t) are transmitted at time (t) and symbols in column (n) are transmitted through antenna (n).

Transmission matrices are formed for transmission of BPSK, QPSK, 8PSK, 16QAM, or 64QAM codes through 3 or 4 transmit antennas.
20   The symbol combinations have orthogonal symbols (s) in at least 2 rows, and the inversions (-s) and conjugates (s*) of the symbols as their elements. For illustration, the transmitter forms a 4x4 matrix out of four symbols for four transmit antennas and transmits them at four times. The 4x4 matrix is built by use of four 2x2 matrices such as equation (7):

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix}$$

25
$$\dots\dots(7)$$

These 2x2 matrices are constituted in the Alamouti scheme. The number of

all possible 4x4 matrices that can be formed in this manner is 24, part of which are shown in equation (8):

$$
\begin{bmatrix} s_1 & s_2 & s_3^{\bullet} & s_4^{\bullet} \\ s_2^{\bullet} & -s_1^{\bullet} & s_4 & -s_3 \\ s_3 & s_4 & -s_1^{\bullet} & -s_2^{\bullet} \\ s_4^{\bullet} & -s_3^{\bullet} & -s_2 & s_1 \end{bmatrix}
\begin{bmatrix} s_1 & s_2 & s_3^{\bullet} & -s_4^{\bullet} \\ s_2^{\bullet} & -s_1^{\bullet} & s_4 & s_3 \\ s_3 & s_4 & -s_1^{\bullet} & s_2^{\bullet} \\ s_4^{\bullet} & -s_3^{\bullet} & -s_2 & -s_1 \end{bmatrix}
\begin{bmatrix} s_1 & s_2 & s_3^{\bullet} & -s_4^{\bullet} \\ s_2^{\bullet} & -s_1^{\bullet} & -s_4 & -s_3 \\ s_3 & s_4 & -s_1^{\bullet} & s_2^{\bullet} \\ s_4^{\bullet} & -s_3^{\bullet} & s_2 & s_1 \end{bmatrix}
\begin{bmatrix} s_1 & s_2 & s_3^{\bullet} & s_4^{\bullet} \\ s_2^{\bullet} & -s_1^{\bullet} & -s_4 & s_3 \\ s_3 & s_4 & -s_1^{\bullet} & -s_2^{\bullet} \\ s_4^{\bullet} & -s_3^{\bullet} & s_2 & -s_1 \end{bmatrix}
$$

$$
\begin{bmatrix} s_1 & s_2 & -s_3^{\bullet} & -s_4^{\bullet} \\ s_2^{\bullet} & -s_1^{\bullet} & s_4 & -s_3 \\ s_3 & s_4 & s_1^{\bullet} & s_2^{\bullet} \\ s_4^{\bullet} & -s_3^{\bullet} & -s_2 & s_1 \end{bmatrix}
\begin{bmatrix} s_1 & s_2 & -s_3^{\bullet} & s_4^{\bullet} \\ s_2^{\bullet} & -s_1^{\bullet} & s_4 & s_3 \\ s_3 & s_4 & s_1^{\bullet} & -s_2^{\bullet} \\ s_4^{\bullet} & -s_3^{\bullet} & -s_2 & -s_1 \end{bmatrix}
\begin{bmatrix} s_1 & s_2 & -s_3^{\bullet} & -s_4^{\bullet} \\ s_2^{\bullet} & -s_1^{\bullet} & -s_4 & s_3 \\ s_3 & s_4 & s_1^{\bullet} & s_2^{\bullet} \\ s_4^{\bullet} & -s_3^{\bullet} & s_2 & -s_1 \end{bmatrix}
\begin{bmatrix} s_1 & s_2 & -s_3^{\bullet} & s_4^{\bullet} \\ s_2^{\bullet} & -s_1^{\bullet} & -s_4 & -s_3 \\ s_3 & s_4 & s_1^{\bullet} & -s_2^{\bullet} \\ s_4^{\bullet} & -s_3^{\bullet} & s_2 & s_1 \end{bmatrix}
$$

$$\ldots\ldots(8)$$

5   where s_1, s_2, s_3 and s_4 are four input symbols.

Some of the arranged symbols are rotated by a predetermined phase prior to transmission. The phase is determined by the minimum coding gain of error matrices so as to maximize diversity gain. An error matrix refers to a matrix having the differences between original symbols and erroneous symbols received at the
10 receiver, and the minimum coding gain is the product of all eigen values of the error matrix.

The phase rotation is implemented once to each of three or four input symbols so that orthogonality is still maintained between the columns of each Alamouti 2x2 matrix. There are 16 phase rotations that satisfy this condition. All
15 possible phase-rotated ones of the first matrix in Eq. (8) are shown in equation (9):

$$
\begin{bmatrix} s_1 & s_2 & vs_3^* & vs_4^* \\ s_2^* & -s_1^* & s_4 & -s_3 \\ s_3 & s_4 & -s_1^* & -s_2^* \\ s_4^* & -s_3^* & -vs_2 & vs_1 \end{bmatrix}
\begin{bmatrix} s_1 & s_2 & s_3^* & s_4^* \\ s_2^* & -s_1^* & vs_4 & -vs_3 \\ s_3 & s_4 & -vs_1^* & -vs_2^* \\ s_4^* & -s_3^* & -s_2 & s_1 \end{bmatrix}
\begin{bmatrix} s_1 & s_2 & vs_3^* & vs_4^* \\ s_2^* & -s_1^* & s_4 & -s_3 \\ s_3 & s_4 & -s_1^* & -s_2^* \\ s_4^* & -s_3^* & -vs_2 & vs_1 \end{bmatrix}
\begin{bmatrix} s_1 & s_2 & s_3^* & s_4^* \\ s_2^* & -s_1^* & vs_4 & -vs_3 \\ s_3 & s_4 & -s_1^* & -s_2^* \\ s_4^* & -s_3^* & -vs_2 & vs_1 \end{bmatrix}
$$

$$
\begin{bmatrix} vs_1 & vs_2 & s_3^* & s_4^* \\ s_2^* & -s_1^* & s_4 & -s_3 \\ vs_3 & vs_4 & -s_1^* & -s_2^* \\ s_4^* & -s_3^* & -s_2 & s_1 \end{bmatrix}
\begin{bmatrix} vs_1 & vs_2 & s_3^* & s_4^* \\ s_2^* & -s_1^* & s_4 & -s_3 \\ s_3 & s_4 & -s_1^* & -s_2^* \\ vs_4^* & -vs_3^* & -s_2 & s_1 \end{bmatrix}
\begin{bmatrix} s_1 & s_2 & s_3^* & s_4^* \\ vs_2^* & -vs_1^* & s_4 & -s_3 \\ vs_3 & vs_4 & -s_1^* & -s_2^* \\ s_4^* & -s_3^* & -s_2 & s_1 \end{bmatrix}
\begin{bmatrix} s_1 & s_2 & s_3^* & s_4^* \\ vs_2^* & -vs_1^* & s_4 & -s_3 \\ s_3 & s_4 & -s_1^* & -s_2^* \\ vs_4^* & -vs_3^* & -s_2 & s_1 \end{bmatrix}
$$

$$
\begin{bmatrix} vs_1 & vs_2 & vs_3^* & vs_4^* \\ s_2^* & -s_1^* & s_4 & -s_3 \\ s_3 & s_4 & -s_1^* & -s_2^* \\ s_4^* & -s_3^* & -s_2 & s_1 \end{bmatrix}
\begin{bmatrix} vs_1 & vs_2 & s_3^* & s_4^* \\ s_2^* & -s_1^* & vs_4 & -vs_3 \\ s_3 & s_4 & -s_1^* & -s_2^* \\ s_4^* & -s_3^* & -s_2 & s_1 \end{bmatrix}
\begin{bmatrix} s_1 & s_2 & vs_3^* & vs_4^* \\ vs_2^* & -vs_1^* & s_4 & -s_3 \\ s_3 & s_4 & -s_1^* & -s_2^* \\ s_4^* & -s_3^* & -s_2 & s_1 \end{bmatrix}
\begin{bmatrix} s_1 & s_2 & s_3^* & s_4^* \\ vs_2^* & -vs_1^* & vs_4 & -vs_3 \\ s_3 & s_4 & -s_1^* & -s_2^* \\ s_4^* & -s_3^* & -s_2 & s_1 \end{bmatrix}
$$

$$
\begin{bmatrix} s_1 & s_2 & s_3^* & s_4^* \\ s_2^* & -s_1^* & s_4 & -s_3 \\ vs_3 & vs_4 & -vs_1^* & -vs_2^* \\ s_4^* & -s_3^* & -s_2 & s_1 \end{bmatrix}
\begin{bmatrix} s_1 & s_2 & s_3^* & s_4^* \\ s_2^* & -s_1^* & s_4 & -s_3 \\ s_3 & s_4 & -vs_1^* & -vs_2^* \\ vs_4^* & -vs_3^* & -s_2 & s_1 \end{bmatrix}
\begin{bmatrix} s_1 & s_2 & s_3^* & s_4^* \\ s_2^* & -s_1^* & s_4 & -s_3 \\ vs_3 & vs_4 & -s_1^* & -s_2^* \\ s_4^* & -s_3^* & -vs_2 & vs_1 \end{bmatrix}
\begin{bmatrix} s_1 & s_2 & s_3^* & s_4^* \\ s_2^* & -s_1^* & s_4 & -s_3 \\ s_3 & s_4 & -s_1^* & -s_2^* \\ vs_4^* & -vs_3^* & -vs_2 & vs_1 \end{bmatrix}
$$

$$\cdots\cdots (9)$$

As noted from the above matrices, the four input symbols s_1, s_2, s_3 and s_4 each rotate one time by a predetermined phase value "v". The phase-rotated matrices

5 are referred to as transmission coding matrices. A total of 384 (=24x16) 4x4n transmission coding matrices can be produced according to the present invention.

FIG. 3 is a block diagram of a transmitter for transmitting one of the transmission coding matrices in the first row of Eq. (9) through four transmit antennas according to an embodiment of the present invention.

10 Referring to FIG. 3, the transmitter includes an S/P converter 110, an encoder 120, phase rotators 130a and 130b, and four transmit antennas 140a to 140d. The S/P converter 110 feeds four input symbols s_1, s_2, s_3 and s_4 in one block to the encoder 120. The encoder 120 produces the first matrix of Eq. (8) from the received one-block symbols. Specifically, the encoder 120 generates four combinations each

15 having four symbol elements from the input four symbols and outputs them one by one at four times. The four symbol combinations correspond to the four rows of the

matrix and the plurality of symbols are transmitted once through their respective antennas at their respective times.

The phase rotators 130a and 130b rotate the phases of two of the four rows received from the encoder 120 by v. When the first transmission coding matrix in Eq. (9) is used, the phase rotators 130a and 130b rotate input symbols by v for transmission at first and fourth times, bypassing symbols for transmission at the other times. The resulting symbols are transmitted to a receiver through the transmit antennas 140a to 140d.

The encoder 120 and the phase rotators 130a and 130b collectively function as a transmission coding matrix generator. While only two rotators 130a and 130b are shown, more rotators can be connected between the encoder 120 and corresponding transmit antennas if other transmission coding matrices are adopted.

A 4x3 transmission coding matrix for three transmit antennas is generated from a 4x4 transmission coding matrix by selecting two of the four columns of the 4x4 matrix, linearly combining the elements of the selected columns, and replacing the selected columns by a column of the linear elements. Six ways ($_4C_2$) can be used to select two of the four columns. For example, 4x3 transmission coding matrices derived from the first matrix of Eq. (8) are shown as equation (10):

$$\begin{bmatrix} (s_1+s_2)/\sqrt{2} & s_3^* & s_4^* \\ (s_2^*-s_1^*)/\sqrt{2} & s_4 & -s_3 \\ (s_3+s_4)/\sqrt{2} & -s_1^* & -s_2^* \\ (s_4^*-s_3^*)/\sqrt{2} & -s_2 & s_1 \end{bmatrix} \begin{bmatrix} s_1 & (s_2+s_3^*)/\sqrt{2} & s_4^* \\ s_2^* & (-s_1^*+s_4)/\sqrt{2} & -s_3 \\ s_3 & (s_4-s_1^*)/\sqrt{2} & -s_2^* \\ s_4^* & (-s_3^*-s_2)/\sqrt{2} & s_1 \end{bmatrix} \begin{bmatrix} s_1 & s_2 & (s_3^*+s_4^*)/\sqrt{2} \\ s_2^* & -s_1^* & (s_4-s_3)/\sqrt{2} \\ s_3 & s_4 & (-s_1^*-s_2^*)/\sqrt{2} \\ s_4^* & -s_3^* & (s_1-s_2)/\sqrt{2} \end{bmatrix}$$

$$\begin{bmatrix} (s_1+s_3^*)/\sqrt{2} & s_2 & s_4^* \\ (s_2^*-s_4)/\sqrt{2} & -s_1^* & -s_3 \\ (s_3-s_1^*)/\sqrt{2} & s_4 & -s_2^* \\ (s_4^*-s_2)/\sqrt{2} & -s_3^* & s_1 \end{bmatrix} \begin{bmatrix} s_1 & (s_2+s_4^*)/\sqrt{2} & s_3^* \\ s_2^* & (-s_1^*-s_3)/\sqrt{2} & s_4 \\ s_3 & (s_4-s_2^*)/\sqrt{2} & -s_1^* \\ s_4^* & (-s_3^*+s_1)/\sqrt{2} & s_2 \end{bmatrix} \begin{bmatrix} s_2 & s_3 & (s_1+s_4^*)/\sqrt{2} \\ -s_1^* & s_4 & (s_2^*-s_3)/\sqrt{2} \\ s_4 & -s_1^* & (s_3-s_2^*)/\sqrt{2} \\ -s_3^* & -s_2 & (s_4^*+s_1)/\sqrt{2} \end{bmatrix}$$

$$\ldots\ldots (10)$$

Similarly, the above matrices are phase-rotated. Thus, a total of 1728 4x3 transmission coding matrices are possible.

5   FIG. 4 is a block diagram of a transmitter for transmitting code symbols in a 4x3 transmission coding matrix produced from the first transmission coding matrix of Eq. (9) according to another embodiment of the present invention.

Referring to FIG. 4, the transmitter includes an S/P converter 210, an encoder 220, rotators 230a and 230b, a column generator 240, and three transmit antennas 250a, 250b and 250c. The S/P converter 210 feeds four input symbols s_1, s_2,

10   s_3 and s_4 in one block to the encoder 220. The encoder 220 produces the first matrix of Eq. (8) from the received one-block symbols. Specifically, the encoder 220 generates four combinations each having four symbol elements from the input four symbols and outputs them one by one over four time periods. The four symbol combinations correspond to the four rows of the matrix and the plurality of symbols

15   are transmitted once through their respective antennas at their respective time periods.

The phase rotators 230a and 230b rotate the phases of two of the four rows received from the encoder 220 by v. When the first transmission coding matrix in Eq.

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(9) is used, the phase rotators 130a and 130b rotate input symbols by v for transmission at first and fourth times, bypassing symbols for transmission at the other times.

The column generator 240 linearly combines the symbol of the second column with the symbol received from the phase rotator 230a at each transmission time and outputs the combined symbol to the transmit antenna 250b. The outputs of the encoder 230, the column generator 240, and the phase rotator 230b are transmitted to the receiver through the transmit antennas 250a, 250b and 250c.

The encoder 220, the phase rotators 230a and 230b, and the column generator 240 collectively function as a transmission coding matrix generator. While only two rotators 230a and 230b are shown and the column generator 240 combines the symbols of the second and third columns, more rotators can be connected between the encoder 220 and corresponding transmit antennas and the column generator 240 can be disposed at a different corresponding position if other transmission coding matrices are adopted.

Examples of desirable transmission coding matrices for three and four transmit antennas are illustrated below.

With respect to a BPSK constellation, the transmission matrix is given in equation (11) by

$$
U_1 = \begin{pmatrix}
s_1 & \dfrac{s_2 + j s_3}{\sqrt{2}} & s_4 \\[2ex]
-s_2^* & \dfrac{s_1^* - j s_4^*}{\sqrt{2}} & s_3^* \\[2ex]
-s_4^* & \dfrac{-s_3^* + j s_2^*}{\sqrt{2}} & s_1^* \\[2ex]
s_3 & \dfrac{-s_4 - j s_1}{\sqrt{2}} & s_2
\end{pmatrix}
$$

for three transmit antennas. For four transmit antennas, the transmission matrix

is

$$U_2 = \begin{pmatrix} s_1 & s_2 & js_3 & s_4 \\ -s_2^* & s_1^* & -js_4^* & s_3^* \\ -s_4^* & -s_3^* & js_2^* & s_1^* \\ s_3 & -s_4 & -js_1 & s_2 \end{pmatrix}$$

$$\ldots \ldots (11)$$

5   With respect to a QPSK constellation, the transmission matrix for three antennas is given in equation (12) by

$$U_3 = \begin{pmatrix} s_1 & \dfrac{s_2 + s_3}{\sqrt{2}} & s_4 \\ -s_2^* & \dfrac{s_1^* - vs_4^*}{\sqrt{2}} & vs_3^* \\ -s_4^* & \dfrac{-s_3^* + s_2^*}{\sqrt{2}} & s_1^* \\ s_3 & \dfrac{-s_4 - vs_1}{\sqrt{2}} & vs_2 \end{pmatrix}$$

where $v = e^{-j2\pi/3}$ for example. For four transmit antennas, the transmission matrix

is

$$U_4 = \begin{pmatrix} s_1 & s_2 & s_3 & s_4 \\ -s_2^* & s_1^* & -vs_4^* & vs_3^* \\ -s_4^* & -s_3^* & s_2^* & s_1^* \\ s_3 & -s_4 & -vs_1 & vs_2 \end{pmatrix}$$

10

where $v = e^{-j2\pi/3}$ for example. $\ldots \ldots (12)$

With respect to an 8PSK constellation, the transmission matrix for three antennas is given in equation (13) by

$$U_5 = \begin{pmatrix} s_1 & \dfrac{s_2+s_3}{\sqrt{2}} & s_4 \\[2mm] -s_2^* & \dfrac{s_1^*-vs_4^*}{\sqrt{2}} & vs_3^* \\[2mm] -s_4^* & \dfrac{-s_3^*+s_2^*}{\sqrt{2}} & s_1^* \\[2mm] s_3 & \dfrac{-s_4-vs_1}{\sqrt{2}} & vs_2 \end{pmatrix}$$

where $v=e^{-j5\pi/6}$ for example. For four transmit antennas, the transmission matrix
5 is

$$U_6 = \begin{pmatrix} s_1 & s_2 & s_3 & s_4 \\ -s_2^* & s_1^* & -vs_4^* & vs_3^* \\ -s_4^* & -s_3^* & s_2^* & s_1^* \\ s_3 & -s_4 & -vs_1 & vs_2 \end{pmatrix}$$

where $v=e^{-j5\pi/6}$ for example.

.....(13)

With respect to a 16QAM constellation, the transmission matrix for three
10 antennas is given in equation (14) by

- 17 -

$$U_7 = \begin{pmatrix} s_1 & \dfrac{s_2+s_3}{\sqrt{2}} & s_4 \\[2ex] -s_2^* & \dfrac{s_1^*-vs_4^*}{\sqrt{2}} & vs_3^* \\[2ex] -s_4^* & \dfrac{-s_3^*+s_2^*}{\sqrt{2}} & s_1^* \\[2ex] s_3 & \dfrac{-s_4-vs_1}{\sqrt{2}} & vs_2 \end{pmatrix}$$

where $v=e^{-j5\pi/12}$ for example. For four transmit antennas, the transmission matrix is

$$U_8 = \begin{pmatrix} s_1 & s_2 & s_3 & s_4 \\ -s_2^* & s_1^* & -vs_4^* & vs_3^* \\ -s_4^* & -s_3^* & s_2^* & s_1^* \\ s_3 & -s_4 & -vs_1 & vs_2 \end{pmatrix}$$

5

where $v=e^{-j5\pi/12}$ for example.

$$\ldots\ldots (14)$$

With respect to a 64QAM constellation, the transmission matrix for three antennas is given in equation (15) by

$$U_9 = \begin{pmatrix} s_1 & \dfrac{s_2+s_3}{\sqrt{2}} & s_4 \\[2ex] -s_2^* & \dfrac{s_1^*-vs_4^*}{\sqrt{2}} & vs_3^* \\[2ex] -s_4^* & \dfrac{-s_3^*+s_2^*}{\sqrt{2}} & s_1^* \\[2ex] s_3 & \dfrac{-s_4-vs_1}{\sqrt{2}} & vs_2 \end{pmatrix}$$

10

where $v=e^{-j7\pi/48}$ for example. For four transmit antennas, the transmission matrix is

- 18 -

$$U_{10} = \begin{pmatrix} s_1 & s_2 & s_3 & s_4 \\ -s_2^* & s_1^* & -v s_4^* & v s_3^* \\ -s_4^* & -s_3^* & s_2^* & s_1^* \\ s_3 & -s_4 & -v s_1 & v s_2 \end{pmatrix}$$

where $v = e^{-j7\pi/48}$ for example.

$$\ldots\ldots(15)$$

Also in accordance with the present invention, described below is a receiver

5　that can decode symbols of the above transmission coding matrices by ML decoding (first embodiment), by super-fast decoding (second embodiment) that renders the ML decoding more efficient, or by sub-optimal decoding (third embodiment).

Decoding according to the First Embodiment

10　FIG. 5 is a block diagram of a receiver that decodes according to an embodiment of the present invention. The receiver is comprised of two independent decoders 340 and 345.

Referring to FIG. 5, a channel estimator 320 estimates channel coefficients representing channel gains from a plurality of transmit antennas to a plurality of

15　receive antennas 310. A symbol arranger 330 collects symbols received from the receive antennas 310 for the four time periods corresponding to transmission by the transmitter illustrated in FIG. 3 or FIG. 4 of one block of symbols at four times.

The symbol arranger 330 forms a matrix out of the collected symbols. In the matrix, symbols received from the same receive antenna are arranged in the same

20　row and symbols received at the same time are arranged in the same column. Although the plurality of receive antennas 310 are illustrated, decoding for the case of one antenna will be described below, for notational simplicity.

If four symbols to be detected are x_1, x_2, x_3 and x_4, the first decoder 340 detects x_1 and x_3 and the second decoder 345 detects x_2 and x_4, based on the channel

gains and the received symbols. Thus, the decoders 340 and 345 detect the four symbols x_1, x_2, x_3 and x_4 simultaneously.

In the first decoder 340, a symbol generator 350 generates all possible symbol pairs and phase rotators 360 and 362 rotate at least one symbol of each

5 symbol pair by the phase value v used in the transmitter or by 1.

A metric calculator 370 calculates the metric values of the resulting phase-rotated symbol pairs. The number of all possible symbol pairs is 2x2 for BPSK, 4x4 for QPSK, 8x8 for 8PSK, 16x16 for 16QAM, and 64x64 for 64QAM. A minimum metric detector 380 detects symbols x_1 and x_3 that have a minimum metric.

10 The second decoder 345 operates in the same manner. After the first and second decoders 340 and 345 detect x_1 & x_3 and x_2 & x_4, respectively, a parallel-to-serial (P/S) converter 390 arranges the detected symbols in the right order and outputs the recovered symbol combination of x_1, x_2, x_3, and x_4.

For notational simplicity, a description will be made below of decoding for

15 BPSK symbols, U_1 illustrated in matrix (11) transmitted from three transmit antennas for the case of one receive antenna, with channel gains from the first, second and third transmit antennas to the receiver of α, β and γ, respectively. The signal r_t received at the receive antenna at time t is given by equation (16):

$$r_1 = \alpha s_1 + \beta \frac{s_2 + s_3}{\sqrt{2}} + \gamma s_4 + n_1 ,$$

20

$$r_2 = -\alpha s_2^* + \beta \frac{s_1^* - j s_4^*}{\sqrt{2}} + \gamma s_3^* + n_2 ,$$

$$r_3 = -\alpha s_4^* + \beta \frac{-s_3^* + j s_2^*}{\sqrt{2}} + \gamma s_1^* + n_3 ,$$

$$r_4 = \alpha s_3 + \beta \frac{-s_4 - j s_1}{\sqrt{2}} + \gamma s_2 + n_4 ,$$

$$..... (16)$$

where s_1, s_2, s_3 and s_4 are symbols transmitted from the transmitter and n_1, n_2, n_3 and n_4 are noise involved with the transmission at the four times. For U_1, the receiver

5 computes symbols x_1, x_2, x_3, and x_4 that minimize the sum as shown in equation (17):

$$\left| r_1 - \left(\alpha x_1 + \beta \frac{x_2 + x_3}{\sqrt{2}} + \gamma x_4 \right) \right|^2 + \left| r_2 - \left(-\alpha x_2^* + \beta \frac{x_1^* - j x_4^*}{\sqrt{2}} + \gamma x_3^* \right) \right|^2 +$$

$$\left| r_3 - \left(-\alpha x_4^* + \beta \frac{-x_3^* + j x_2^*}{\sqrt{2}} + \gamma x_1^* \right) \right|^2 + \left| r_4 - \left(\alpha x_3 + \beta \frac{-x_4 - j x_1}{\sqrt{2}} + \gamma x_2 \right) \right|^2$$

$$..... (17)$$

10 The sum decomposes into two parts. The first part contains only x_1 and x_3 and the second part contains only x_2 and x_4. Thus, the receiver illustrated in FIG. 5 is constituted by decoupling the first decoder 340 for decoding the pair of x_1 and x_3 from the second decoder 345 for decoding the pair of x_2 and x_4.

The above operation for the transmission coding matrices U_1, U_3, U_5, U_7 and

15 U_9 transmitted from three transmit antennas will be described in more detail.

For ML decoding for U_1, as shown in equation (18), letting

$$R_1 = \alpha^* r_1 + \beta \frac{1}{\sqrt{2}} r_2^* + \gamma r_3^* + j \beta^* \frac{1}{\sqrt{2}} r_4$$

$$R_3 = \gamma r_2^* - j \beta^* \frac{1}{\sqrt{2}} r_1 + \alpha^* r_4 - \beta^* \frac{1}{\sqrt{2}} r_3^*$$

$$R_{13} = \frac{j(C_1 + C_3)}{2}$$

20 $$C_1 = -\alpha^* \beta \sqrt{2} - \alpha \beta^* \sqrt{2}$$

$$C_3 = j\gamma^* \beta\sqrt{2} - j\gamma\beta^*\sqrt{2}$$

$$\ldots\ldots(18)$$

the first decoder 340 minimizes the sum as shown in equation (19):

$$|R_1 - x_1|^2 + |R_3 - x_3|^2 + |R_{13} - x_1^* x_3|^2$$

$$\ldots\ldots(19)$$

over all possible symbol pairs and detects the minimizing symbol pair x_1 and x_3.

Similarly, as shown in equation (20), letting

$$R_2 = \beta^* \frac{1}{\sqrt{2}} r_1 - \alpha r_2^* + j\beta \frac{1}{\sqrt{2}} r_3^* + \gamma^* r_4$$

$$R_4 = \gamma^* r_1 - j\beta \frac{1}{\sqrt{2}} r_2^* - \alpha r_3^* - \beta^* \frac{1}{\sqrt{2}} r_4$$

$$R_{24} = \frac{j(C_2 + C_4)}{2}$$

$$C_2 = \alpha\beta^*\sqrt{2} + \alpha^*\beta\sqrt{2}$$

$$C_4 = j\gamma\beta^*\sqrt{2} - j\gamma^*\beta\sqrt{2}$$

$$\ldots\ldots(20)$$

the second decoder 345 minimizes the sum as shown in equation (21):

$$|R_2 - x_2|^2 + |R_4 - x_4|^2 + |R_{24} - x_2^* x_4|^2$$

$$\ldots\ldots(21)$$

over all the possible symbol pairs and detects the minimizing symbol pair x_2 and x_4.

For ML decoding for U_3 or U_5, as shown in equation (22), letting

$$R_1 = \alpha^* r_1 + \beta \frac{1}{\sqrt{2}} r_2^* + \gamma r_3^* - v^* \beta^* \frac{1}{\sqrt{2}} r_4$$

$$R_3 = v\gamma r_2^* + \beta^* \frac{1}{\sqrt{2}} r_1 + \alpha^* r_4 - \beta \frac{1}{\sqrt{2}} r_3^*$$

$$R_{13} = -\frac{(C_1 + C_3)}{2}$$

$$C_1 = -\alpha^* \beta v \sqrt{2} + \alpha \beta^* \sqrt{2}$$

$$C_3 = \gamma \beta^* v \sqrt{2} - \gamma^* \beta \sqrt{2}$$

. . . . . (22)

5   where v is the phase value by which the phase of a symbol is rotated, $e^{-j2\pi/3}$ for U_3 and $e^{-j5\pi/6}$ for U_5, for example, the first decoder 340 minimizes the sum as shown in equation (23):

$$|R_1 - x_1|^2 + |R_3 - x_3|^2 + |R_{13} - x_1^* x_3|^2$$

. . . . . (23)

10   over all possible symbol pairs and detects the minimizing symbol pair x_1 and x_3.

Similarly, as shown in equation (24), letting

$$R_2 = \beta^* \frac{1}{\sqrt{2}} r_1 - \alpha r_2^* + \beta \frac{1}{\sqrt{2}} r_3^* + v^* \gamma^* r_4$$

$$R_4 = \gamma^* r_1 - v\beta \frac{1}{\sqrt{2}} r_2^* - \alpha r_3^* - \beta^* \frac{1}{\sqrt{2}} r_4$$

$$R_{24} = -\frac{(C_2 + C_4)}{2}$$

15

$$C_2 = -\alpha \beta^* \sqrt{2} + v\alpha^* \beta \sqrt{2}$$

$$C_4 = -v\gamma \beta^* \sqrt{2} + \gamma^* \beta \sqrt{2}$$

. . . . . (24)

the second decoder 345 minimizes the sum as shown in equation (25):

$$|R_2 - x_2|^2 + |R_4 - x_4|^2 + |R_{24} - x_2^* x_4|^2$$

20

. . . . . (25)

over all the possible symbol pairs and detects the minimizing symbol pair x_2 and x_4.

For ML decoding for U_7 or U_9, as shown in equation (26), letting

$$R_1 = \frac{\left(\alpha^* r_1 + \beta \frac{1}{\sqrt{2}} r_2^* + \gamma r_3^* - v^* \beta^* \frac{1}{\sqrt{2}} r_4\right)}{K_3}$$

$$R_3 = \frac{\left(v\gamma r_2^* + \beta^* \frac{1}{\sqrt{2}} r_1 + \alpha^* r_4 - \beta \frac{1}{\sqrt{2}} r_3^*\right)}{K_3}$$

$$R_{13} = -\frac{(C_1 + C_3)}{2K_3}$$

$$K_3 = |\alpha|^2 + |\beta|^2 + |\gamma|^2$$

$$C_1 = -\alpha^* \beta v \sqrt{2} + \alpha \beta^* \sqrt{2}$$

$$C_3 = \gamma \beta^* v \sqrt{2} - \gamma^* \beta \sqrt{2}$$

$$\ldots \ldots (26)$$

where $v = e^{-j5\pi/12}$ for U_7 and $v = e^{-j7\pi/48}$ for U_9, for example, the first decoder 340 minimizes the sum as shown in equation (27):

$$|R_1 - x_1|^2 + |R_3 - x_3|^2 + |R_{13} - x_1^* x_3|^2 - |x_1|^2 |x_3|^2$$

$$\ldots \ldots (27)$$

over all possible symbol pairs and detects the minimizing symbol pair x_1 and x_3.

Similarly, as shown in equation (28), letting

$$R_2 = \frac{\left(\beta^* \frac{1}{\sqrt{2}} r_1 - \alpha r_2^* + \beta \frac{1}{\sqrt{2}} r_3^* + v^* \gamma^* r_4\right)}{K_3}$$

$$R_4 = \frac{\left(\gamma^* r_1 - \nu\beta\frac{1}{\sqrt{2}} r_2^* - \alpha r_3^* - \beta^*\frac{1}{\sqrt{2}} r_4\right)}{K_3}$$

$$R_{24} = -\frac{(C_2 + C_4)}{2K_3}$$

$$C_2 = -\alpha\beta^*\sqrt{2} + \nu\alpha^*\beta\sqrt{2}$$

$$C_4 = -\nu\gamma\beta^*\sqrt{2} + \gamma^*\beta\sqrt{2}$$

$$\dots\dots(28)$$

the second decoder 345 minimizes the sum as shown in equation (29):

$$|R_2 - x_2|^2 + |R_4 - x_4|^2 + |R_{24} - x_2^* x_4|^2 - |x_2|^2 |x_4|^2$$

$$\dots\dots(29)$$

over all the possible symbol pairs and detects the minimizing symbol pair x_2 and x_4.

Now, ML decoding for modulation symbols transmitted from four transmit antennas will be described with reference to one receive antenna, with channel gains from the first to fourth transmit antennas to the receiver of α, β, γ, and ξ, respectively.

For ML decoding for U_2, as shown in equation (30), letting

$$R_1 = \alpha^* r_1 + \beta r_2^* + \zeta r_3^* + j\gamma^* r_4$$

$$R_3 = \zeta r_2^* - j\gamma^* r_1 + \alpha^* r_4 - \beta r_3^*$$

$$R_{13} = -(C_1 + C_3)$$

$$C_1 = j\alpha^*\gamma + j\alpha\gamma^*$$

$$C_3 = \zeta^*\beta - \zeta\beta^*$$

$$\dots\dots(30)$$

the first decoder 340 minimizes the sum as shown in equation (31):

$$|R_1 - x_1|^2 + |R_3 - x_3|^2 + |R_{13} - x_1 x_3^*|^2$$

$$\dots\dots(31)$$

over all possible symbol pairs and detects the minimizing symbol pair x_1 and x_3.

Similarly, as shown in equation (32), letting

$$R_2 = \beta^* r_1 - \alpha r_2^* + j\gamma r_3^* + \zeta^* r_4$$

$$R_4 = \zeta^* r_1 - j\gamma r_2^* - \alpha r_3^* - \beta^* r_4$$

5
$$R_{24} = -(C_2 + C_4)$$

$$C_2 = \zeta\beta^* - \zeta^*\beta$$

$$C_4 = -j\alpha\gamma^* - j\gamma\alpha^*$$

$$\dots\dots(32)$$

10 the second decoder 345 minimizes the sum as shown in equation (33):

$$|R_2 - x_2|^2 + |R_4 - x_4|^2 + |R_{24} - x_2 x_4^*|^2$$

$$\dots\dots(33)$$

over all the possible symbol pairs and detects the minimizing symbol pair x_2 and x_4.

15   For ML decoding for U_4 or U_6, as shown in equation (34), letting

$$R_1 = \alpha^* r_1 + \beta r_2^* + \zeta r_3^* - v^* \gamma^* r_4$$

$$R_3 = v\zeta r_2^* + \gamma^* r_1 + \alpha^* r_4 - \beta r_3^*$$

$$R_{13} = -(C_1 + C_3)$$

$$C_1 = -\alpha^* \gamma v + \alpha\gamma^*$$

20
$$C_3 = \zeta\beta^* v - \zeta^*\beta$$

$$\dots\dots(34)$$

where $v = e^{-j2\pi/3}$ for U_4 and $v = e^{-j5\pi/6}$ for U_6, for example, the first decoder 340 minimizes the sum as shown in equation (35):

$$|R_1 - x_1|^2 + |R_3 - x_3|^2 + |R_{13} - x_1^* x_3|^2$$

$$\ldots \ldots (35)$$

over all possible symbol pairs and detects the minimizing symbol pair x_1 and x_3.

Similarly, as shown in equation (36), letting

$$R_2 = \beta^* r_1 - \alpha r_2^* + \gamma r_3^* + v^* \zeta^* r_4$$

$$R_4 = \zeta^* r_1 - v\gamma r_2^* - \alpha r_3^* - \beta^* r_4$$

$$R_{24} = -(C_2 + C_4)$$

$$C_2 = -\alpha \gamma^* + v\alpha^* \gamma$$

$$C_4 = -v\zeta \beta^* + \zeta^* \beta$$

$$\ldots \ldots (36)$$

the second decoder 345 minimizes the sum as shown in equation (37):

$$|R_2 - x_2|^2 + |R_4 - x_4|^2 + |R_{24} - x_2^* x_4|^2$$

$$\ldots \ldots (37)$$

over all the possible symbol pairs and detects the minimizing symbol pair x_2 and x_4.

For ML decoding for U_8 or U_{10}, as shown in equation (38), letting

$$R_1 = \frac{(\alpha^* r_1 + \beta r_2^* + \zeta r_3^* - v^* \gamma^* r_4)}{K_4}$$

$$R_3 = \frac{(v\zeta r_2^* + \gamma^* r_1 + \alpha^* r_4 - \beta r_3^*)}{K_4}$$

$$R_{13} = -\frac{(C_1 + C_3)}{K_4}$$

$$K_4 = |\alpha|^2 + |\beta|^2 + |\gamma|^2$$

$$C_1 = -\alpha^* \gamma v + \alpha \gamma^*$$

$$C_3 = \zeta\beta^* v - \zeta^* \beta \qquad \qquad \ldots (38)$$

where $v = e^{-j5\pi/12}$ for U_8 and $v = e^{-j7\pi/48}$ for U_{10}, for example, the first decoder 340 minimizes the sum as shown in equation (39):

$$|R_1 - x_1|^2 + |R_3 - x_3|^2 + |R_{13} - x_1^* x_3|^2 - |x_1|^2 |x_3|^2$$

5
$$\ldots (39)$$

over all possible symbol pairs and detects the minimizing symbol pair x_1 and x_3.

Similarly, as shown in equation (40), letting

$$R_2 = \frac{(\beta^* r_1 - \alpha r_2^* + \gamma r_3^* + v^* \zeta^* r_4)}{K_4}$$

$$R_4 = \frac{(\zeta^* r_1 - v\gamma r_2^* - \alpha r_3^* - \beta^* r_4)}{K_4}$$

10

$$R_{24} = -\frac{(C_2 + C_4)}{K_4}$$

$$C_2 = -\alpha\gamma^* + v\alpha^* \gamma$$

$$C_4 = -v\zeta\beta^* + \zeta^* \beta \qquad \qquad \ldots (40)$$

the second decoder 345 minimizes the sum as shown in equation (41):

$$|R_2 - x_2|^2 + |R_4 - x_4|^2 + |R_{24} - x_2^* x_4|^2 - |x_2|^2 |x_4|^2$$

15
$$\ldots (41)$$

over all the possible symbol pairs and detects the minimizing symbol pair x_2 and x_4.

Decoding according to the Second Embodiment

20   For ML decoding according to the first embodiment, the metric values of all possible symbol pairs must be computed to detect desired symbols. Thus, 8x8 metric calculations are required for 8PSK, and 16x16 metric calculations for 16QAM.

These codes can be decoded very quickly by reducing the number of required computations utilizing the characteristics of PSK and QAM.

FIGs. 6A, 6B and 6C illustrate BPSK, QPSK, and 8PSK signal constellations, respectively. As shown, all PSK modulation symbols lie on a unit

5 circle, which implies that their length is always 1.

For U_6, since x_1 and x_3 both have length 1, as shown in equation (42), minimizing the metric (35) is equivalent to minimizing

$$|R_1 - x_1|^2 + |R_3 - x_3|^2 + |x_1 R_{13} - x_3|^2$$

10

$$\ldots\ldots(42)$$

For each fixed x_1, as shown in equation (43), minimizing the sum of equation (42) is equivalent to minimizing

$$|(R_3 + x_1 R_{13}) - x_3|^2$$

$$\ldots\ldots(43)$$

15 Since x_1 is fixed, minimizing the metric of equation (43) is equivalent to finding the closest constellation point x_3 to $R_3 + x_1 R_{13}$. It is possible to have one x_3 for each x_1. Thus, the receiver detects a symbol pair (x_1, x_3) that minimizes the ML decoding metric of the first embodiment as desired reception symbols. For x_2 and x_4, the receiver similarly finds the closest constellation point x_4 to $R_4 + x_2 R_{24}$ and detects

20 a symbol pair (x_2, x_4) that minimizes the ML decoding metric as desired x_2 and x_4. The same procedure is applied to other PSK transmission coding matrices.

With regard to QAM decoding, all 16QAM or 64QAM symbols have different lengths, as illustrated in FIGs. 7a and 7B, and the metric (39) is used for QAM codes. When x_1 is fixed, as shown in equation (44), minimizing the metric

25 (39) over all possible values for x_3 is equivalent to minimizing

$$|(R_3 + x_1 R_{13}) - x_3|^2 + |R_1 - x_1|^2$$

$$\ldots\ldots(44)$$

For each fixed x_1, minimizing the metric of equation (44) is equivalent to finding the closest constellation point x_3 to $R_3 + x_1 R_{13}$. Thus, the receiver detects all symbol pairs (x_1, x_3) and detects the minimizing symbol pair (x_1, x_3). For x_2 and x_4, the receiver similarly finds the closest constellation point x_4 to $R_4 + x_2 R_{24}$ and detects

5 the minimizing symbol pair (x_2, x_4). The same procedure is applied to other QAM transmission coding matrices.

FIG. 8 is a flowchart illustrating the second embodiment of decoding according to the present invention. While the procedure is described as being performed for detection of only one symbol pair, it is to be noted that the other

10 symbol pairs are detected in the same manner.

Referring to FIG. 8, thresholds m_1 and m_2 are set to a very small number, for example, 10^{-10} and symbol index i is set to 0 in step 402. The receiver computes parameters R_1, R_2, and R_{13} using signals received for a plurality of time periods and estimated channel gains in step 404. In step 406, a first symbol x_1 is set to s_i. The

15 receiver computes $g(x_1) = R_3 + x_1 R_{13}$ in step 408. The receiver sets variable j to an initial value 0 in step 410, sets a second symbol x_3 to s_j in step 412, and computes $A(x_3) = |g(x_1) - x_3|^2$ in step 414.

In step 416, $A(x_3)$ is compared with threshold m_1. If $A(x_3)$ is equal to or greater than threshold m_1, the receiver proceeds to step 420. On the contrary, if $A(x_3)$

20 is less than m_1, m_1 is updated to $A(x_3)$ and $y(x_3)$ is set as x_3 in step 418. In step 420, it is determined whether x_3 is the last symbol, for example, if i=16 for 16QAM. If it is, it is determined that the second symbol s_j matching the first symbol s_i has been detected and the receiver proceeds to step 424. Otherwise, the receiver increases variable j by 1 in step 422 and returns to step 412.

25 In step 424, the receiver computes

$B(x_3) = |R_1 - x_1|^2 + |R_3 - y(x_3)|^2 + |R_{13} - x_1^* y(x_3)|^2$. If $B(x_3)$ is equal to or greater than threshold m_2, the receiver proceeds to step 430. Otherwise, it proceeds to step 428.

The receiver updates m_2 to $B(x_3)$ and sets $y(x_1)$ as x_1 in step 428. In step 430, it is determined whether x_1 is the last symbol, for example, if i=16 for 16QAM. If it is, it is determined that the second symbols s_j matching all first symbols s_i have been detected and the receiver proceeds to step 434. Otherwise, the receiver increases variable i by 1 in step 432 and returns to step 406. In step 434, the receiver finally detects $y(x_1)$ and $y(x_3)$.

FIG. 9 is a block diagram of a receiver that decodes according to the second embodiment of the present invention. The receiver is comprised of two independent decoders 540 and 545.

Referring to FIG. 9, a channel estimator 520 estimates channel coefficients representing channel gains from a plurality of transmit antennas to a plurality of receive antennas 510. A symbol arranger 530 collects symbols received from the receive antennas 510 for the four time periods corresponding to transmission by the transmitter illustrated in FIG. 3 or FIG. 4 of one block of symbols at four times.

The symbol arranger 530 forms a matrix out of the collected symbols. In the matrix, symbols received from the same receive antenna are arranged in the same row and symbols received at the same time are arranged in the same column. Although the plurality of receive antennas 510 are illustrated, decoding for the case of one antenna will be described below, for notational simplicity.

If four symbols to be detected are x_1, x_2, x_3 and x_4, the first decoder 540 detects x_1 and x_3 and the second decoder 545 detects x_2 and x_4, based on the channel gains and the received symbols. Thus, the decoders 540 and 545 detect the four symbols x_1, x_2, x_3 and x_4 simultaneously.

In the first decoder 540, a symbol generator 550 generates all possible symbol pairs and phase rotators 552 and 554 rotate at least one symbol of each symbol pair by the phase value v used in the transmitter or by 1. The number of all possible symbol pairs is the square of a modulation order used, for example, 16^2 for

16QAM.

A symbol selector 560 computes the parameters R_1, R_3, and R_{13} and selects symbol pairs that minimize the metric (43) or (44) according to the parameters. The number of the selected symbol pairs is equal to the modulation order. For example,

5   16 symbol pairs are selected according to the metric (44), for 16QAM.

A metric calculator 570 calculates the metric values of the selected symbol pairs using the parameters according to a modulation scheme and the number of the transmit antennas. A minimum metric detector 580 detects one symbol pair having a minimum metric value using the computed metric values. The metric computation is

10   performed by Eq. (19), (23), (27), (31), (35) or (39) shown above.

The second decoder 545 operates in the same manner. After the first and second decoders 540 and 545 detect x_1 & x_3 and x_2 & x_4, respectively, a P/S converter 590 arranges the detected symbols in the right order and outputs the recovered symbol combination of x_1, x_2, x_3, and x_4.

15   Assuming a 2^b PSK signal constellation, once R_1, R_3 and R_{13} are computed, b summations and 2^b multiplications are required for computation of $g(x_1)$, 2^b comparisons, one for each $g(x_1)$, are required for computing $y(x_3)$, and finally 3×2^b multiplications and additions are performed for computing $B(x_3)$. Therefore, the same symbol detection performance as that of the ML decoding according to the

20   first embodiment can be achieved with a total of 4×2^b additions and multiplications and 2^b comparisons according to the second embodiment of the present invention.

Decoding according to the Third Embodiment

QPSK or 8PSK symbols can be decoded with a reduced volume of

25   computations despite a lower symbol detection performance, as compared to decoding methods according to the first and second embodiments.

For 8PSK symbols, the receiver computes the parameters R_1, R_3 and R_{13} and

finds the closest constellation points q_1 to R_1, q_3 to R_3, and q_{13} to R_{13}. If $q_{13}=q_1^*q_3$, the receiver outputs q_1 and q_3.

If not, the receiver computes an angle Φ_d by dividing the angle between q_{13} and $q_1^*q_3$ by 2. Then the receiver searches for desired first and second symbols by

5   calculating the ML decoding metric values of first symbol and second symbol candidates whose angles are respectively within the angular distance Φ_d from q_1 and q_3.

Similarly, the receiver computes the parameters R_2, R_4 and R_{24} and finds the closest constellation points q_2 to R_2, q_4 to R_4, and q_{24} to R_{24}. If $q_{24}=q_2^*q_4$, the receiver

10   outputs q_2 and q_4.

If not, the receiver computes an angle Φ_d' by dividing the angle between q_{24} and $q_2^*q_4$ by 2. Then the receiver searches for desired first and second symbols by calculating the ML decoding metric values of first symbol and second symbol candidates whose angles are respectively within the angular distance Φ_d' from q_2

15   and q_4.

FIGs. 10A and 10B illustrate 8PSK signal constellations to depict sub-optimal decoding according to the present invention. Referring to FIG. 10A, the closest constellation point q_1 to R_1 is $e^{j(3\pi/4)}$, the closest constellation point q_3 to R_3 is $e^{j(-\pi/4)}$, and the closest constellation point q_{13} to R_{13} is $e^{j(\pi/4)}$. $q_1^*q_3$ is $e^{j(\pi)}$ and $\Phi_d'=3\pi/8$.

20   Referring to FIG. 10B, the receiver searches for a symbol pair that minimizes the ML decoding metric over all possible symbol pairs made out of first symbol candidates s_2, s_3 and s_4 which are within $3\pi/8$ from q_1 and second symbol candidates s_0, s_6 and s_7 which are within $3\pi/8$ from q_3. The same process is applied to other PSK transmission coding matrices.

25   FIG. 11 is a flowchart illustrating decoding according to the third embodiment of the present invention. For notational simplicity, the decoding is carried out for only one symbol pair.

Referring to FIG. 11, the receiver computes the parameters R_1, R_3 and R_{13} in step 602 and finds the closest constellation points x_1 to R_1, x_3 to R_3, and x_{13} to R_{13} in step 604. If $x_{13} = x_1^* x_3$ in step 606, the receiver outputs x_1 and x_3.

If not, the receiver computes $\Phi_d = \frac{1}{2} \angle \left(\frac{x_{13}}{x_1^* x_3} \right)$ in step 608 and selects

5　first symbol and second symbol candidates whose angles are respectively within the angular distance Φ_d from x_1 and x_3 in step 610. In step 612, the receiver detects a symbol pair that minimizes the ML decoding metric of the first embodiment by calculating the ML decoding metric values of all possible symbol pairs made out of the first and second symbol candidates.

10　For the sub-optimal decoding, the receiver is configured in hardware as illustrated in FIG. 9. The symbol selector 560 computes the parameters R_1, R_3 and R_{13}, finds the closest constellation points to R_1, R_3, and to R_{13}, computes the angle Φ_d, and selects candidate symbols within Φ_d from the constellation points. For QPSK, up to 3x3 candidate symbol pairs are produced from the candidate symbols

15　and for 8PSK, the number of the candidate symbol pairs is up to 5x5.

The metric calculator 570 calculates the metric values of the symbol pairs using Eq. (19), (23), (27), (31), (35), or (39) and the minimum metric detector 580 detects one symbol pair having a minimum metric value.

The second decoder 545 operates in the same manner. Thus, the first

20　decoder 540 detects x_1 and x_3 and the second decoder 545 detects x_2 and x_4. The P/S converter 590 arranges the detected symbols in the right order and outputs the recovered symbol combination of x_1, x_2, x_3 and x_4.

FIGs. 12, 13 and 14 are graphs illustrating SER versus SNR from ML decoding for BPSK, QPSK, and 8PSK, respectively, assuming 2, 3 and 4 transmit

25　antennas and, for example, one receive antenna in the first embodiment of the present invention.

In FIG. 12, reference numerals 700, 702 and 704 denote SERs for 2, 3, and 4 transmit antennas, respectively. In FIG. 13, reference numerals 710, 712 and 714 denote SERs for 2, 3, and 4 transmit antennas, respectively. In FIG. 14, reference numerals 720, 722 and 724 denote SERs for 2, 3, and 4 transmit antennas,

5 respectively.

The relation between SER and SNR is given by equation (45):

$$SER = C \cdot SNR^{-d}$$

$$\ldots \ldots (45)$$

where C is a constant and d is a diversity gain. Therefore, $\log(SER) = -d \cdot \log(C \cdot SNR)$

10 in FIGs. 12, 13 and 14. With $\log(SNR)$ on an X axis, $y = -dx$. Thus, d is the inclination. In other words, the inclination of the SER-SNR graph on a log scale is the diversity gain. As noted from FIGs. 12, 13 and 14, the transmit diversity of the present invention offers a diversity order equal to the number of transmit antennas, that is, a maximum diversity order.

15 FIG. 15 is a graph comparing SERs between the decoding schemes of the first and third embodiments for four transmit antennas transmitting 8PSK symbols according to the present invention. Reference numeral 732 denotes the sub-optimal decoding according to the third embodiment and reference numeral 730 denotes the ML decoding according to the first embodiment. The sub-optimal decoding still

20 provides a maximum diversity gain despite a slightly degraded performance as compared to the ML decoding.

As described above, the present invention advantageously provides a maximum diversity gain for space-time block codes with three or more transmit antennas and simplifies the structure of a decoder for detecting transmission

25 symbols in a receiver. Therefore, a data processing rate is increased and system development cost is saved.

While the invention has been shown and described with reference to certain preferred embodiments thereof, it will be understood by those skilled in the art that

various changes in form and details may be made therein without departing from the spirit and scope of the invention as defined by the appended claims.